

UNCLASSIFIED

Defense Technical Information Center
Compilation Part Notice

ADP011611

TITLE: Tensor Polarizabilities of Magnetoelectric Particles on the Base of Strip-Line-Coupled Magnetostatic Wave Resonators

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: International Conference on Electromagnetics of Complex Media [8th], Held in Lisbon, Portugal on 27-29 September 2000. Bianisotropics 2000

To order the complete compilation report, use: ADA398724

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP011588 thru ADP011680

UNCLASSIFIED

Tensor Polarizabilities of Magnetoelectric Particles on the Base of Strip-Line-Coupled Magnetostatic Wave Resonators

S. V. Zagriadski

Radiophysics Department, St. Petersburg State Technical University
Polytekhnicheskaya 29, St. Petersburg, 195251, Russia
Fax: (7-812) 247-20-88, E-mail: zagr@radio.stu.neva.ru

Abstract

An electrodynamic description of bianisotropic particles on the base of strip-line-coupled magnetostatic wave (MSW) resonators is developed and analytical closed-form expressions for their tensor polarizabilities are obtained for an arbitrary direction of a magnetizing field and an arbitrary resonator shape. Numerical calculations are performed for a normally magnetized thin-ferrite-film disk resonator with a metal strip on its surface.

1. Introduction

Recently proposed composite non-reciprocal bianisotropic materials [1] represent ensembles of magnetized thin-ferrite-film magnetostatic wave resonators with surface metallization. Induced electric and magnetic dipole moments \mathbf{p}_e and \mathbf{p}_m of such artificial particles are related to the external electric and magnetic fields as

$$\mathbf{p}_e = \tilde{\alpha}_{ee} \mathbf{E} + \tilde{\alpha}_{em} \mathbf{H}, \quad \mathbf{p}_m = \tilde{\alpha}_{me} \mathbf{E} + \tilde{\alpha}_{mm} \mathbf{H}, \quad (1)$$

where $\tilde{\alpha}_{ee}$, $\tilde{\alpha}_{em}$, $\tilde{\alpha}_{me}$ and $\tilde{\alpha}_{mm}$ are corresponding tensor polarizabilities. Although a nature and qualitative physical picture of magnetoelectric coupling in these elements is quite obvious and an experimental evidence of the effect has been obtained [2], the electrodynamic description of the

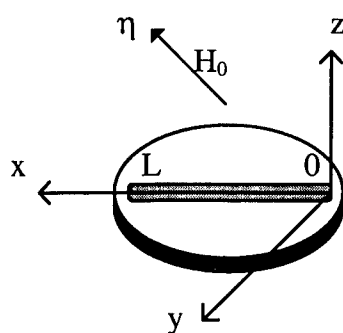


Fig. 1

particles and quantitative evaluation of magnetoelectric coupling till the present time has not been performed. In this paper we consider a thin-ferrite-film resonator with a linear metal strip of the width b on its surface, as shown in the Fig.1 for a disk resonator magnetized by the field H_0 in an arbitrary direction η . Dimensions of the resonator are much less than a wavelength in the surrounding media with the permittivity ϵ , so electric and magnetic fields in (1) can be assumed uniform and quasi-static. Magnetization of oscillation modes \mathbf{m}_q for the type q and corresponding eigenfrequencies ω_q are supposed to be known, as well the ferromagnetic resonance linewidths

ΔH_q . The approach is based on the earlier obtained solutions of self-consistent electrodynamic problems of the excitation of one-port [3] and two-port [4] MSW resonators. In this formulation, in particular, dipole moments of a particle, induced by an external magnetic field are found through a resonator high-frequency magnetization, which is determined taking into account the "back" influence of the current in the strip on this magnetization. Neglecting of this interaction results in the non-accurate determination of the polarizabilities $\tilde{\alpha}_{em}$, $\tilde{\alpha}_{mm}$ and their resonant frequency. Presented electrodynamic description of magnetoelectric particles enables to obtain constitutive relations for composite media in a closed form.

2. Self-Consistent Electrodynamic Problem for $\tilde{\alpha}_{em}$ and $\tilde{\alpha}_{mm}$ Determination

Tensor polarizabilities $\tilde{\alpha}_{em}$ and $\tilde{\alpha}_{mm}$ are calculated in the assumption that $\mathbf{E} = 0$ in (1). Magnetization induced by a given magnetic field \mathbf{H} is found as an expansion into the series of eigenmodes

$$\mathbf{M} = \sum_q c_q \mathbf{m}_q, \quad c_q = \varphi_q \int_V (\mathbf{H} + \mathbf{h}_\mu) \cdot \mathbf{m}_q^* dV, \quad (2)$$

where
$$\varphi_q = -\frac{b_q}{\omega^2 - \omega_q^2 - i\omega_q^2 Q_q^{-1}}, \quad b_q = \frac{i(\omega + \omega_q)\omega_M}{\Phi_q}, \quad \Phi_q = \int_V [\mathbf{m}_q \times \mathbf{m}_q^*]_\eta dV,$$

$$Q_q = \frac{H_0}{2\Delta H_q}, \quad \omega_M = \gamma\mu_0 M_0, \quad \gamma \text{ is the gyromagnetic ratio, } \mu_0 \text{ is the permeability of free space, } M_0$$

is the saturation magnetization, and V is the resonator volume. The "back" influence of a strip current on the magnetization is taken into account by including the magnetic field \mathbf{h}_μ in (2), which can be found as a field of a transmission line excited by an equivalent given magnetic current $i\omega\mathbf{M}$

$$\mathbf{h}_\mu = c_\mu(x)\mathbf{H}_\mu^r + c_{-\mu}(x)\mathbf{H}_{-\mu}^r, \quad (3)$$

with

$$c_\mu(x) = -\frac{i\omega\omega_0}{N_\mu^r} \int_0^x dx \int_S (\mathbf{M} \cdot \mathbf{H}_{-\mu}^r) dS, \quad c_{-\mu}(x) = -\frac{i\omega\omega_0}{N_\mu^r} \int_x^L dx \int_S (\mathbf{M} \cdot \mathbf{H}_{-\mu}^r) dS$$

where $\mathbf{H}_\mu^r = \mathbf{H}_\mu + \Gamma_2 \mathbf{H}_{-\mu}$, $\mathbf{H}_{-\mu}^r = \mathbf{H}_{-\mu} + \Gamma_1 \mathbf{H}_\mu$, $N_\mu^r = (1 - \Gamma_1 \Gamma_2) N_\mu$, $\mathbf{H}_{\pm\mu} = \mathbf{H}_{\pm\mu 0}(y, z) \exp(\mp i\beta x)$ is the magnetic field of a dominant wave in a strip-line (in the absence of ferrite) with the propagation constant β , N_μ is a normalization coefficient [4], Γ_1 and Γ_2 are the reflection coefficients for a strip current at $x = 0$ and $x = L$ ($\Gamma_1 = -1$ and $\Gamma_2 = -\exp(-2i\beta L)$ for our case of an open transmission line), and S is the cross section of the line. The system of integral equations (2), (3), formulating a self-consistent electrodynamic problem, has the following solution for amplitudes of electromagnetic waves in the transmission line

$$c_\mu(x) = \left[(e^{i\beta x} - 1) - \Gamma_1 (e^{-i\beta x} - 1) \right] c_{\mu 0}, \quad c_{-\mu}(x) = \left[(e^{-i\beta x} - e^{-i\beta L}) - \Gamma_1 (e^{i\beta x} - e^{i\beta L}) \right] c_{\mu 0}, \quad (4)$$

where
$$c_{\mu 0} = -\frac{i\omega\mu_0}{N_\mu} \left[i\beta(1 - \Gamma_1 \Gamma_2) + 2s \frac{i\omega\mu_0}{N_\mu} \varphi_q |I_{\mu q}|^2 \right]^{-1} I_{\mu q}^* \varphi_q \int_V (\mathbf{H} \cdot \mathbf{m}_q^*) dV, \quad I_{\mu q} = \int_S (\mathbf{H}_{\mu 0} \cdot \mathbf{m}_q^*) dS$$

and parameter s , depending on the line length, is given in [4] ($s \approx 2i\beta L^2$ for a special case $\beta L \ll 1$). Substituting (4) in (3) and using Ampere's law (an integration extends over an arbitrary contour C in the cross section yz which includes the strip)

$$\oint_C \mathbf{h}_\mu d\mathbf{l} = J(x),$$

one can find an induced electric dipole moment and using (2) - a magnetic dipole moment

$$\mathbf{p}_e = \frac{1}{i\omega} \mathbf{e}_x \int_0^L J(x) dx, \quad \mathbf{p}_m = \sum_q c_q \int_V \mathbf{m}_q dV. \quad (5)$$

Polarizabilities can be written in a tensor form

$$\tilde{\alpha}_{em} = A \cdot \begin{bmatrix} m_{qx}^* & m_{qy}^* & m_{qz}^* \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \tilde{\alpha}_{mm} = B \cdot \begin{bmatrix} m_{qx} m_{qx}^* & m_{qx} m_{qy}^* & m_{qx} m_{qz}^* \\ m_{yx} m_{qx}^* & m_{qy} m_{qy}^* & m_{qy} m_{qz}^* \\ m_{qz} m_{qx}^* & m_{qz} m_{qy}^* & m_{qz} m_{qz}^* \end{bmatrix}, \quad (6)$$

where for the case $\beta L \ll 1$ coefficients A and B are the following

$$A = \frac{i}{6} \frac{\mu_0}{\sqrt{2WN_\mu}} \varphi_q I_{\mu q}^* V \beta^2 L^3 \left(-\beta + L \frac{\omega \mu_0}{N_\mu} \varphi_q |I_{\mu q}|^2 \right)^{-1}, \quad (7)$$

$$B = \varphi_q V^2 + \varphi_q^2 V^2 |I_{\mu q}|^2 \frac{\omega \mu_0 \beta^3 L^4}{3N_\mu} \left[i\beta(1 - \Gamma_1 \Gamma_2) + 2s\varphi_q |I_{\mu q}|^2 \frac{i\omega \mu_0}{N_\mu} \right]^{-1}, \quad (8)$$

and W is a characteristic impedance of a transmission line, which can be calculated as [5]

$$W = \frac{120}{\sqrt{\epsilon}} \left(\ln \frac{2.2L}{b} - 1 \right). \quad (9)$$

For a normally magnetized ferrite disk and a fundamental uniform mode of magnetization (when its components can be assumed to be $m_{qx} = 1$, $m_{qy} = -i$, $m_{qz} = 0$) calculated polarizability coefficients A (7) are shown in the Fig.2. Note that in this case an internal biasing magnetic field is uniform. The diameter of the resonator is taken equal to the length of a strip and the particle is characterized by the following set of parameters: $L = 0.5\text{mm}$, $b = 20\mu\text{m}$, $4\pi M_0 = 1750$ Oe, $H_0 = 5320$ Oe, $2\Delta H_0 = 0.5$ Oe, $\epsilon = 10$.

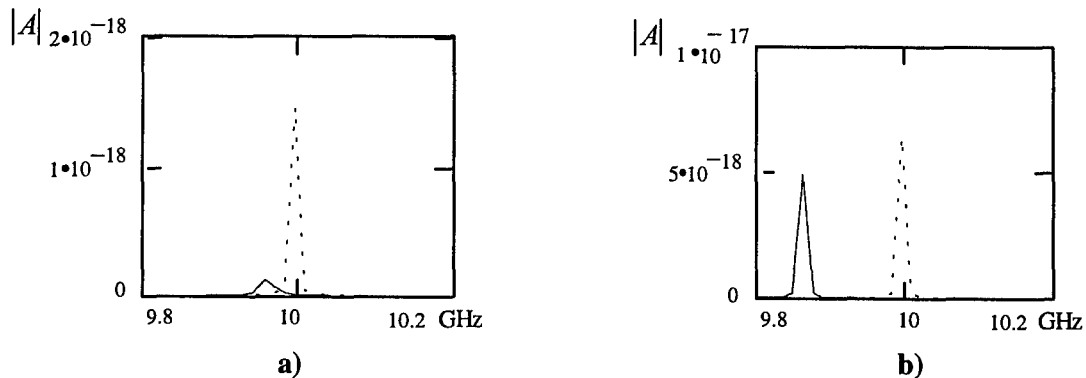


Fig. 2 Polarizability coefficient $|A|$ (ferrite film thickness: a) $10\mu\text{m}$, b) $50\mu\text{m}$). Solid curve: Self-consistent solution; Dotted: "Back" coupling neglected.

3. Calculation of Tensor Polarizabilities $\tilde{\alpha}_{ee}$ and $\tilde{\alpha}_{me}$

Tensor polarizabilities $\tilde{\alpha}_{ee}$ and $\tilde{\alpha}_{me}$ are calculated in the assumption that $\mathbf{H} = 0$ in (1). A current distribution along a narrow strip in an external longitudinal electric field \mathbf{E} is known from the antenna theory [5]

$$J(x) = J(L/2)f(x), \quad (10)$$

where $J(L/2) = \frac{2iE}{\beta W \cos(\beta L/2)} \left(1 - \cos \frac{\beta L}{2} \right)$, $f(x) = \frac{\cos \beta(x - L/2) - \cos(\beta L/2)}{1 - \cos(\beta L/2)}$. Induced electric dipole moment \mathbf{p}_e is obtained by integrating the current $J(x)$ according (5). A magnetic dipole moment

\mathbf{p}_m of the ferrite resonator is excited by the current (10) and can be calculated using (5) with the amplitude coefficients c_q being obtained from (2) for $\mathbf{H} = 0$. It can be easily seen that the magnetic field of the transmission line is related to the current as

$$\mathbf{h}_\mu = \frac{J(x)}{J_c} \mathbf{H}_{\mu 0}, \quad (11)$$

where $J_c = \oint_C \mathbf{H}_{\mu 0} d\mathbf{l}$ (for this value the following relationship is valid $J_c = \sqrt{N_\mu / (2W)}$).

Performing calculations we come to the following polarizabilities for the case $\beta L \ll 1$

$$\tilde{\alpha}_{ee} = C \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \tilde{\alpha}_{me} = D \cdot \begin{bmatrix} m_{qx} & 0 & 0 \\ m_{qy} & 0 & 0 \\ m_{qz} & 0 & 0 \end{bmatrix}, \quad (12)$$

where $C = \frac{1}{6} \frac{\beta L^3}{\omega W}$, $D = \frac{i\beta L^3}{6W} \frac{\varphi_q I_{\mu q} V}{J_c}$.

4. Conclusion

Derived explicit expressions for polarizabilities show that all non-zero tensor elements, except $\tilde{\alpha}_{ee}$, have resonant character with resonance frequencies close, but not equal, to the MSW resonator eigenfrequencies. Elements of tensors of magnetoelectric coupling $\tilde{\alpha}_{em}$, $\tilde{\alpha}_{me}$ are proportional to the saturation magnetization M_0 of ferrite and to the third power of the strip length L^3 and increase with the growth of the resonator quality factor Q . For low magnetic losses these tensors are related as $\tilde{\alpha}_{em} \approx \mu_0 \tilde{\alpha}_{me}^*$. Elements of the tensor $\tilde{\alpha}_{mm}$ are proportional to the resonator volume V . The tensor $\tilde{\alpha}_{ee}$ has no frequency dependence and is proportional to the third power of the strip length L^3 . In the case when a ferrite resonator has a non-elliptic form (e.g., a straight-edge MSW resonator with a film of a rectangular form), calculations of polarizabilities must be carried out taking into account the influence of nonuniformity of the internal biasing magnetic field [6].

References

- [1] E. O. Kamenetskii, "On the technology of making chiral and bianisotropic waveguides for microwave propagation", *Microwave and optical technology letters*, Vol. 11, No. 2, pp. 103-107, 1996.
- [2] E. O. Kamenetskii, I. Awai, and A. K. Saha, "Experimental evidence for magnetoelectric coupling in a ferromagnetic resonator with surface metallization", *Microwave and optical technology letters*, Vol. 24, No. 1, pp. 56-60, 2000.
- [3] S. V. Zagriadski, "Design theory for magnetostatic wave filters and delay lines / Theory of one port magnetostatic wave resonators", *20th European Microwave Conference Proceedings*, Vol. 2, pp. 1263-1268, 1990.
- [4] S. V. Zagriadski, "Theory and applications of multiport structures using magnetostatic waves", *22nd European Microwave Conference Proceedings*, Vol. 2, pp. 1363-1368, 1992.
- [5] S. A. Schelkunoff, *Advanced Antenna Theory*. New York, 1952.
- [6] S. V. Bogachev and S. V. Zagriadski, "Influence of internal field nonuniformity on frequency spectrum of straight-edge forward volume magnetostatic wave resonator", *Journal of Communications Technology and Electronics*, Vol. 44, No. 7, pp. 802-806, 1999.